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RAPID COMMUNICATION

Possible juvenile Palaeoarchaean TTG magmatism in eastern India and its constraints for the evolution of the Singhbhum craton

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Abstract

High-precision SHRIMP U–Pb zircon dating yields a late Palaeoarchaean age (3290 ± 8.6 Ma) for a large, unmetamorphosed, weakly peraluminous TTG body (the Keonjhargarh–Bhaunra pluton) in the Singhbhum craton of eastern India. One inherited subhedral zircon grain gave a concordant age of 3495.9 ± 5.3 Ma and Nd isotope characteristics show a juvenile trend with $\varepsilon Nd_t \sim 0$ and T_{DM} 3395–3453 Ma. The data support a model of typical Archaean crustal evolution until late Palaeoarchaean times for the Singhbhum craton, which is in contrast to the more southerly Bastar craton where Palaeoarchaean non-TTG granites have been identified. These data demonstrate the diachronous development of continental crustal blocks now forming the basement of the eastern and central peninsular of India.

Keywords: Singhbhum craton, Palaeoarchaean, SHRIMP, Nd-isotopes

1. Introduction

The Singhbhum craton of northeastern India (Fig. 1a, b) contains one of the oldest rock successions in the world (Saha, 1994; Mukhopadhyay, 2001) comparable in age only with the Isua Greenstone Belt of Greenland, the Abitibi Belt of Ontario and Quebec, the Coonterunah Group of the Pilbara craton and the Onverwacht Group of the Kaapvaal craton (e.g. Compston *et al.* 1986; Nutman, Fryer & Bridgewater, 1989; Armstrong *et al.* 1990; Nutman *et al.* 1997, 2004; Lowe & Byerly, 1999; Dauphas *et al.* 2007). Palaeoarchaean cratonic fragments have also been identified elsewhere in India. The Bastar craton, which borders the southern margin of the Singhbhum, contains granite–greenstone terranes up to 3.56 Ga as documented by Pb–Pb zircon ages for tonalite–trondhjemite–granodiorite gneisses (TTG; Ghosh, 2004) and U–Pb zircon ages for a non-TTG granite (Rajesh *et al.* 2009), whilst ∼3.34 Ga felsites have been identified in the Dharwar craton (Naqvi, 2005). Existence of older crust is supported by detrital zircon ages of ∼3.58 Ga in the Dharwar craton supracrustal rocks (Nutman *et al.* 1992; Peucat *et al.* 1995) and of ∼3.6 Ga in metasediments of the Older Metamorphic Group of the Singhbhum craton (Goswami *et al.* 1995). Whilst the presence of Archaean age successions in the Singhbhum craton has been known for many years (Saha, 1994), high precision geochronological data are relatively scarce and so our understanding of the geological evolution of this craton remains poorly constrained.

Here we present geochemical, isotope geochemical and petrographic data from the Keonjhargarh–Bhaunra granite, exposed to the north and east of the city of Keonjhargarh (21° 47′ 7.8″ N, 85° 47′ 35.5″ W; Fig. 1b; Saha, 1994) and covering a minimum of 2000 km^2. Outcrop conditions are poor owing to anthropogenic activity, forestation and Holocene deposits.

2. Geology

The Keonjhargarh–Bhaunra granite (Saha, 1994) is part of the Meso- to Palaeoarchaean Singhbhum batholith, which is composed of 12 different plutons that have only in part been studied with regard to their geochemistry and petrography (Saha, 1994). These granites form the core of the Singhbhum craton and are thought to have intruded during up to three phases of magmatic activity: phases I and II (the Type A granites after Saha *et al.* 1984) at 3.3 Ga and phase III (or Type B granites) at 3.1 Ga (Moorbath, Taylor & Jones, 1986; Mishra *et al.* 1999). The basement rocks that occur now as enclaves comprise the Older Metamorphic Group and the Older Metamorphic Tonalite Gneiss. The Singhbhum granite batholith is surrounded by BIF-bearing greenstone successions of the Iron Ore Group in three detached outcrop belts. Relative ages of the Singhbhum granite batholith and the low metamorphic grade Iron Ore Group supracrustals, and their relationship to the Older Metamorphic Group and Older Metamorphic Tonalite Gneiss, however, remain controversial, due largely to the lack of high precision radiometric ages of the various complexes. Some authors

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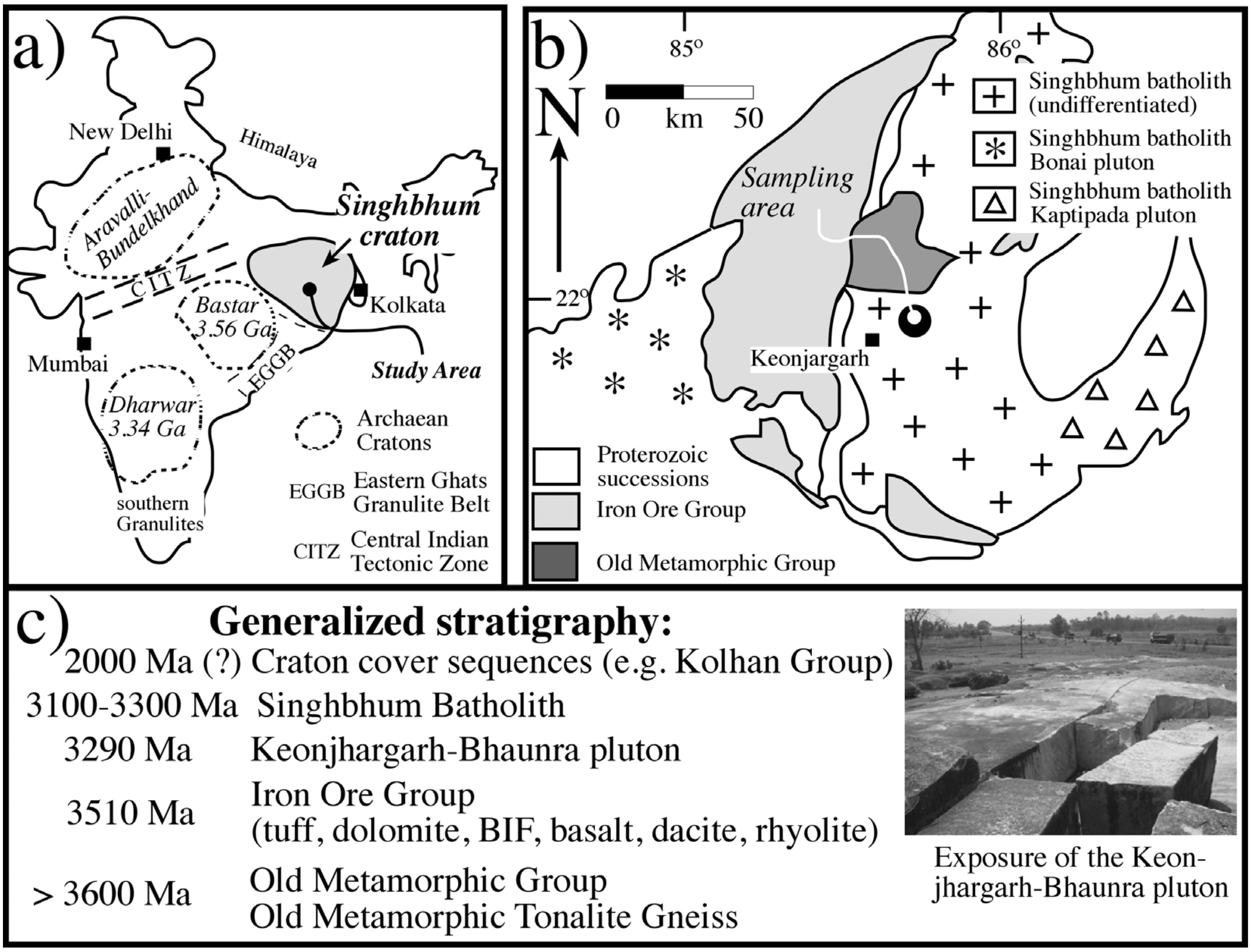

Figure 1. (a) Study area location in India with the main Archaean cratonic areas. (b) Schematic geological map of the Singhbhum craton. (c) Generalized stratigraphy of the oldest successions of the Singhbhum craton and a field impression.

consider the Singhbhum granite batholith to be the basement to the Iron Ore Group, others consider that intrusion was after deposition of the Iron Ore Group, whilst yet others think deposition of the Iron Ore Group occurred between intrusion phases II and III (see review by Mukhopadhyay, 2001). The Older Metamorphic Group and Older Metamorphic Tonalite Gneiss are considered to be around 3.6 to 3.4 Ga old (Mishra *et al*. 1999) and represent the oldest geological units in the craton. However, U–Pb zircon ages of 3507 ± 2 Ma recently obtained from dacitic lava of the southern Iron Ore Group (Mukhopadhyay *et al*. 2008) clearly indicate these lavas are older than any of the Singhbhum granites that have so far been dated. However, it is important to note that three separate Iron Ore Group belts exist in the Singhbhum craton, located in the Tomka–Daitari Basin in the south, the Gorumahishani–Badampahar Basin to the northeast and the western Jamda–Koira Basin. According to some authors, all these basins belong to a single group. Others, however, suggest subdivision of the sequences into older and younger sedimentary successions (see Ghosh & Mukhopadhyay, 2007).

Field exposures of the Keonjhargarh-Bhaunra pluton are fresh (Fig. 1c) and show primary magmatic textures with no evidence for any regional or local deformation or alteration (Saha, 1994). Mishra *et al*. (1999) report Pb–Pb ages from Singhbum Granite close to the present sampling area, and obtained a mean age of 3328 ± 7 Ma from a total of only four zircon grains (one of which was from the Keonjhargarh granite) using the Cameca ims-4f ion microprobe. However, variations within single grains and between different grains were large (ranging from 3169 to 3346 Ma). Here, we present a high precision U–Pb SHRIMP age based on nine concordant results for the pluton in this region in conjunction with detailed geochemical and isotope geochemical analyses.

3. Petrology of the Keonjhargarh–Bhaunra pluton

The granitic rock comprises mainly plagioclase and quartz with subordinated microcline. Both feldspars appear altered and partly sericitized. Quartz is medium to fine grained, while plagioclase is fine grained and mostly subhedral (*c*. 70 % of the grains). Alkali feldspar is medium to coarse grained and less abundant than plagioclase, with plagioclase (P) to alkali feldspar (F) ratios of 0.7 (P/F). Accessory primary minerals are amphibole (grain size <0.1 mm), biotite and very fine-grained orthopyroxene. Muscovite occurs only in highly altered feldspar grains. Zircon can be observed in thin-section with sizes up to 150 μm. The rock does not show a foliated texture or any other metamorphic or deformational textures.

4. Geochemistry

Major element analysis indicates a weak peraluminous nature of the granite with aluminium saturation index (ASI) values (after Frost *et al*. 2001) around 1, with one sample having a slightly higher value of 1.1 (Table 1). The granite shows moderate silica concentrations (*c*. 72 %), low K_2O/Na_2O ratios (<1), low Ni (<5 ppm), but enriched Cr concentrations (136–160 ppm) and Th, Rb and U concentrations below typical continental crust (McLennan, Taylor & Hemming,

Table 1. Geochemical analyses of the samples from the Keonjhargarh–Bhaunra pluton

		K1	K2	K3	K4	K5
		Fine to medium-grained plagioclase-rich granitic rock with few mafic minerals (amphibole, orthopyroxene)				
MALI		6.92	6.49	6.92	4.91	6.63
ASI*		1	1.1	1	1	1
CIA		53	50	51	51	50
Fe no.		0.8	0.8	0.8	0.8	0.8
SiO_2	wt %	72.90	72.60	72.90	72.30	71.90
Al_2O_3	wt %	14.37	13.91	13.92	14.64	14.18
Fe_2O_{3t}	wt %	1.35	1.75	1.87	1.76	1.81
MgO	wt %	0.26	0.39	0.37	0.45	0.44
CaO	wt %	0.94	1.40	1.23	2.03	1.57
Na_2O	wt %	4.41	4.64	3.96	4.89	4.72
K_2O	wt %	3.45	3.25	4.19	2.05	3.48
TiO_2	wt %	0.16	0.18	0.26	0.18	0.26
P_2O_5	wt %	0.04	0.05	0.07	0.06	0.10
MnO	wt %	0.02	0.02	0.03	0.03	0.03
LOI	wt %	1.00	0.90	0.90	0.70	0.80
SUM	wt %	99.00	99.20	99.70	99.10	99.30
Ba	ppm	446.00	443.00	476.00	274.00	712.00
Rb	ppm	83.00	83.00	101.00	71.00	93.00
Sr	ppm	338.00	288.00	273.00	401.00	449.00
Cs	ppm	2.30	2.40	2.20	2.50	4.50
Cr	ppm	160.00	144.00	151.00	136.00	154.00
V	ppm	16.00	11.00	17.00	21.00	18.00
Ni	ppm	3.20	2.90	5.00	3.30	4.10
Co	ppm	1.90	1.60	2.70	2.30	2.80
Cu	ppm	2.40	2.80	2.80	10.30	40.50
Nb	ppm	5.10	4.90	8.10	5.30	7.10
Ta	ppm	0.30	0.50	0.30	0.30	0.40
Y	ppm	5.80	4.50	5.20	9.70	7.50
Zr	ppm	135.00	123.00	208.00	131.00	144.00
Hf	ppm	3.50	3.20	5.20	3.70	3.40
Th	ppm	9.80	10.00	17.70	10.30	11.80
U	ppm	1.10	1.30	1.20	1.60	1.30
Pb	ppm	11.30	10.40	12.50	9.80	9.80
Ga	ppm	16.40	16.00	15.60	19.10	16.80
Zn	ppm	36.00	37.00	49.00	46.00	45.00
La	ppm	32.00	29.00	55.00	32.00	42.00
Ce	ppm	59.00	54.00	111.00	62.00	81.00
Pr	ppm	5.63	5.05	10.85	6.15	7.76
Nd	ppm	18.70	16.40	36.50	19.70	19.20
Sm	ppm	2.48	2.15	4.66	3.40	2.72
Eu	ppm	0.55	0.48	0.77	0.80	0.73
Gd	ppm	1.48	1.25	2.48	2.40	1.92
Tb	ppm	0.21	0.17	0.32	0.38	0.32
Dy	ppm	0.92	0.78	1.08	1.61	1.28
Ho	ppm	0.16	0.13	0.12	0.27	0.22
Er	ppm	0.42	0.36	0.36	0.75	0.51
Tm	ppm	0.06	0.06	0.06	0.11	0.07
Yb	ppm	0.41	0.38	0.33	0.67	0.48
Lu	ppm	0.06	0.06	0.05	0.10	0.06
Ce/Ce*		1.06	1.08	1.10	1.07	1.08
Eu/Eu*		0.85	0.87	0.67	0.80	0.85
La_N/Yb_N		51.66	50.80	110.70	31.51	58.09

Normalization ('N') after chondritic values and calculation of Ce* and Eu* are after Taylor & McLennan (1985).
Wt % – weight per cent; ppm – parts per million; CIA – chemical index of alteration, calculated after Nesbitt & Young (1982); * – not corrected for apatite; MALI – modified alkali-lime index after Frost *et al.* (2001); ASI – aluminium saturation index; Fe no. – $FeO^{tot}/(FeO^{tot} + MgO)$ after Frost *et al.* (2001) LOI – loss on ignition; SUM – sum of oxide weight percentages.

2006; Table 1). As such, the granite could be classified as a calc-alkaline I-type granite. Alteration of the rock is low with chemical index of alteration (CIA) values close to 50 (Table 1; after Nesbitt & Young, 1982). The MALI indices (modified alkali-lime index; Frost *et al.* 2001) for the samples are between 6 and 8. The granites are alkali-calcic to calc-alkalic. The Frost *et al.* (2001) to classify granitic suites. The rocks from Keonjhargarh–Bhaunra have Fe-numbers ($FeO^{tot}/(FeO^{tot} + MgO)$) around 0.8, and, therefore, are classified as ferrous granites and would fall in the field of arc granites according to their silica content (Frost *et al.* 2001).

The granites are relatively enriched in large ion lithophile elements (LILE), such as Rb, Ba, Cs (Table 1; Fig. 2a) and in incompatible elements such as light rare earth elements (La, Ce), Zr, Hf and Th. Significant depletion can be observed in Ta, Nb and Ti (Fig. 2a). The Rb/Ba (0.2), Rb/Sr (0.25) and Y/Nb (1.1) ratios are low, but Sr/Ba ratios are around 0.8, which is typical for partial melting in the presence of fluids and cannot be related to melt regimes resulting from fractionation of upper crustal material (Harris & Inger, 1992).

Rare earth element (REE) concentrations (Fig. 2b), normalized to chondrite, show a typical granitic pattern, but without a significant negative Eu anomaly, reflecting the

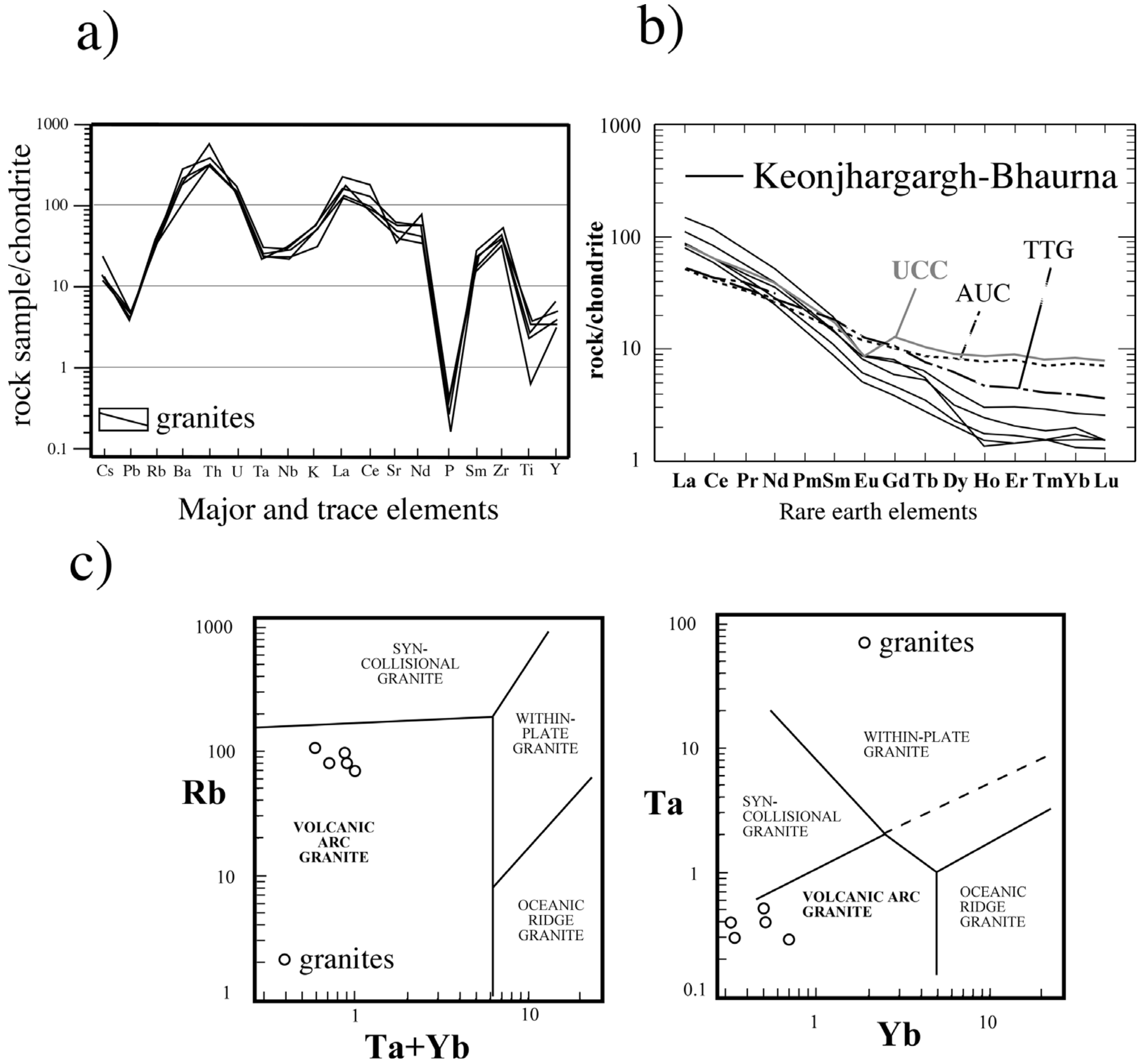

Figure 2. (a) Major and trace element concentrations of the samples normalized to chondritic values after Sun & McDonough (1989). (b) Chondritic normalization after Taylor & McLennan (1985) of rare earth elements from the Keonjhargarh–Bhaunra pluton; values for UCC (typical modern upper continental crust) and AUC (Archaean upper crust) after McLennan, Taylor & Hemming (2006), and TTG (tonalite–trondhjemite–granodiorite) values after Rollinson (2006) are shown for reference. (c) Tectonic discrimination diagrams for granites (Pearce, Harris & Tindle, 1984).

abundant plagioclase identified petrographically. The Eu/Eu* values lie between 0.8 and 0.87, with the exception of one sample, which is close to a typical Archaean value (0.95 after McLennan, Taylor & Hemming, 2006). The slope of the pattern (La_N/Yb_N between 31 and 111; Table 1; Fig. 2b) demonstrates the depletion in heavy REE and enrichment in light REE.

Trace element concentrations (e.g. Nb, Y and Rb) suggest a volcanic arc palaeotectonic setting (Fig. 2c), and the strong negative anomalies of Nb, Ta and Ti (Fig. 2a) are similar to those observed in modern continental arc magmas (Hofmann, 1988, 1997). In Archaean times, however, TTG magmas were typically intruded prior to stabilization of the crust (Drummond & Defant, 1990) and thought to have been generated by partial melting of hydrated basalt. In such melting processes, low Nb/La ratios are associated with low Ti/Zr ratios (Rapp & Watson, 1995; Kemp & Hawkesworth, 2003; Hawkesworth & Kemp, 2006). Large crustal formation events with the production of TTG batholiths can be observed in many Palaeoarchaean cratons, for example the Kaapvaal craton of South Africa (De Wit *et al*. 1992). According to its geochemical signature, the Keonjhargarh–Bhaunra pluton, therefore, is a typical Archaean TTG rock (Fig. 3) and shows a modern arc signature (Fig. 2a, c). Light REE of the Keonjhargarh–Bhaunra pluton resemble typical average upper crust (AUC) but the heavy REE are depleted when compared to typical TTG values (Fig. 2b; after Kamber *et al*. 2002) and typical Archaean crust (after McLennan, Taylor & Hemming, 2006). Thus it seems possible that the magma had a metasedimentary source at depth, thus enabling TTG-like geochemical signatures with stable garnet in the residue.

5. Isotope geochemistry

5.a. U–Pb dating

Zircon grains were separated and hand selected for U–Pb dating using a SHRIMP-II ion microprobe (see online Appendix 1 at http://www.journals.cambridge.org/geo for analytical methods). Most grains are euhedral, show

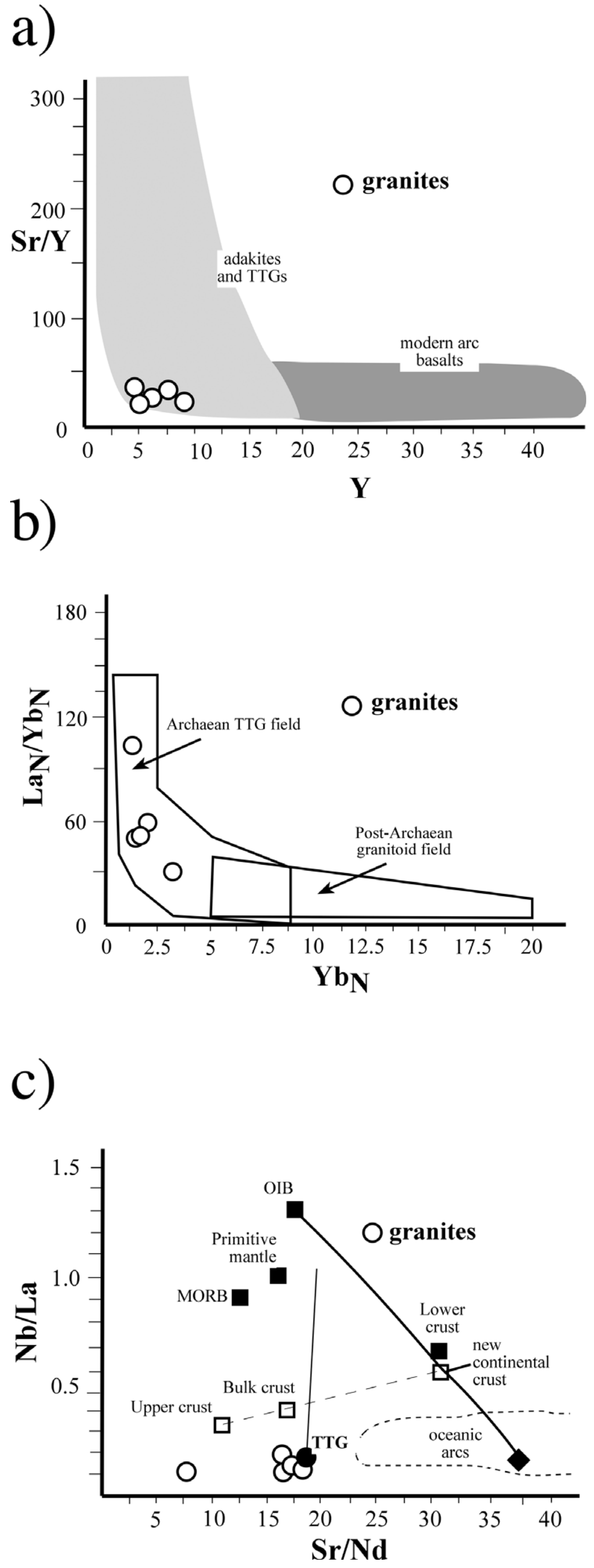

Figure 3. (a) Sr/Y versus Y diagram to decipher the type of granitic magma (Münker *et al*. 2004). (b) Plot of La/Yb versus Yb (normalized to chondrite, denoted by ‘N’) after Martin (1986). (c) Sr/Nd versus Nb/La ratios to characterize the magma composition. The samples plot very close to the typical TTG composition (Hawkesworth & Kemp, 2006).

well-developed magmatic structures and are brownish to clear in colour with rarely occurring inclusions (Fig. 4 inset). The grains vary in form, from elongate to short prismatic crystals. Some grains are anhedral and may be inherited. A total of 20 zircon crystals were analysed in this study, one of which was anhedral (KJR11.1) and yielded the oldest concordant age of 3496 ± 5 Ma. Nine zircons analysed have less than 5 % discordance and yield a mean concordia age of 3291 ± 9 Ma (Fig. 4; Table 2; MSWD = 0.51). The remaining ten grains give results of varying concordance (ranging from 5 to 39 % discordant) and provide a poorly defined lower intercept age of about 900 Ma (MSWD = 14). The only known Meso-Neoproterozoic magmatic event in the region is the poorly dated Newer Dolerite Swarm (Saha, 1994). However, given the poor reliability of this lower intercept age, the possibility of multiple U–Pb systematics, which may have disturbed the isotopic system, and the lack of high-precision ages for any Meso-Neoproterozoic magmatic or thermal event in the Singhbhum craton, the lower intercept age cannot be further interpreted.

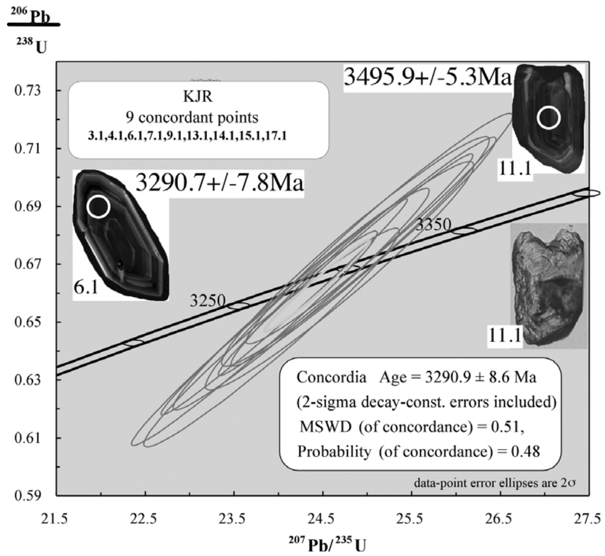

Figure 4. Probability plot of the concordant age using nine concordant zircon grains. Insets show the oldest grain (11.1), which is inherited, and one example of a zircon yielding concordant results (6.1). See online Appendix 1 for more information on analytical methods. Photos of the zircons can be supplied by the main authors.

5.b. Nd isotope analysis

Neodymium isotope measurements have been carried out on two samples in order to determine the character of the magma which produced this granite. The ratios for the two samples for ^{143}Nd/^{144}Nd are 0.51061 and 0.51024, and for ^{147}Sm/^{144}Nd 0.10426 and 0.08575. The calculated initial values of ^{143}Nd/^{144}Nd are 0.50834 and 0.50837 (Table 3). Given that the εNd$_{today}$ values for these Nd isotope ratios are −40 and −47, respectively, this leads to T_{DM} of 3452 Ma and 3394 Ma (after DePaolo, 1981). As εNd$_t$ are close to 0 (Table 3) the Keonjhargarh–Bhaunra pluton can be considered to be relatively juvenile.

6. Interpretation and discussion

The new petrographic, geochemical and isotope geochemical data of a weakly peraluminous pluton in eastern India points to the influence of juvenile magmas for this TTG-type granite body with inherited Early Palaeoarchaean zircons. T_{DM} values show a mantle extraction event only 100–150 Ma before emplacement of the granite. This

Table 2. U–Pb isotope values from zircon SHRIMP analyses

Spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm $^{206}Pb^*$	(1) $^{206}Pb/^{238}U$ Age (Ma)		(2) $^{206}Pb/^{238}U$ Age (Ma)		(3) $^{206}Pb/^{238}U$ Age (Ma)		(1) $^{207}Pb/^{206}Pb$ Age (Ma)		% d	Total $^{238}U/^{206}Pb$	±%	Total $^{207}Pb/^{206}Pb$	±%	(1) $^{238}U/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	±%	err corr
KJR12.1	0.38	380	247	0.67	147.0	2384	±46	2155	±51	2390	±50	3105.8	±7.1	30	2.224	2.3	0.24087	0.41	2.232	2.3	0.23780	0.44	14.67	2.4	0.4470	2.3	0.982
KJR2.1	0.06	482	180	0.39	201.0	2552	±50	2248	±55	2556	±52	3314.0	±4.6	30	2.057	2.4	0.27183	0.29	2.059	2.4	0.27135	0.29	18.17	2.4	0.4860	2.4	0.992
KJR5.1	0.41	469	65	0.14	167.0	2227	±44	1984	±46	2232	±45	3102.6	±5.9	39	2.411	2.3	0.24055	0.33	2.421	2.3	0.23729	0.37	13.50	2.4	0.4126	2.3	0.988
KJR8.1	0.07	300	201	0.69	144.0	2853	±54	2662	±69	2864	±58	3221.3	±5.5	13	1.794	2.3	0.25641	0.34	1.796	2.3	0.25583	0.35	19.64	2.4	0.5570	2.3	0.989
KJR18.1	0.87	187	87	0.48	78.3	2540	±50	2288	±55	2545	±53	3218.0	±12.0	27	2.047	2.3	0.26210	0.42	2.065	2.4	0.25500	0.73	16.99	2.5	0.4830	2.4	0.955
KJR1.1	0.11	97	47	0.50	52.9	3154	±60	3044	±95	3159	±63	3297.0	±8.9	5	1.582	2.4	0.26940	0.54	1.584	2.4	0.26840	0.56	23.36	2.5	0.6310	2.4	0.973
KJR3.1	0.12	90	46	0.53	52.3	3323	±62	3362	±140	3325	±66	3291.0	±9.4	−1	1.480	2.4	0.26850	0.56	1.482	2.4	0.26740	0.60	24.87	2.5	0.6740	2.4	0.970
KJR4.1	0.05	235	182	0.80	135.0	3305	±61	3318	±130	3304	±65	3294.7	±5.7	0	1.492	2.3	0.26854	0.35	1.493	2.3	0.26806	0.36	24.76	2.4	0.6700	2.3	0.988
KJR6.1	0.05	115	59	0.54	64.9	3259	±61	3231	±110	3260	±64	3290.7	±7.8	1	1.519	2.4	0.26780	0.49	1.519	2.4	0.26740	0.50	24.26	2.4	0.6580	2.4	0.979
KJR7.1	0.04	274	109	0.41	154.0	3249	±60	3217	±110	3250	±62	3284.6	±5.1	1	1.525	2.3	0.26665	0.32	1.526	2.3	0.26633	0.33	24.06	2.4	0.6550	2.3	0.990
KJR9.1	0.02	129	50	0.40	74.9	3323	±62	3352	±140	3326	±64	3297.0	±7.5	−1	1.482	2.4	0.26860	0.47	1.483	2.4	0.26840	0.48	24.96	2.4	0.6740	2.4	0.981
KJR10.1	0.30	139	62	0.46	75.0	3130	±59	3002	±90	3141	±61	3306.5	±8.2	6	1.593	2.4	0.27260	0.46	1.598	2.4	0.27010	0.52	23.28	2.4	0.6250	2.4	0.976
KJR13.1	0.08	108	73	0.70	59.9	3207	±61	3129	±00	3210	±65	3301.0	±8.6	3	1.549	2.4	0.26980	0.54	1.551	2.4	0.26910	0.55	23.92	2.5	0.6450	2.4	0.975
KJR14.1	0.11	202	168	0.86	112.0	3206	±59	3138	±100	3213	±65	3289.0	±6.5	3	1.549	2.4	0.26800	0.40	1.551	2.4	0.26710	0.41	23.73	2.4	0.6440	2.4	0.985
KJR15.1	0.10	70	47	0.69	40.4	3290	±62	3284	±130	3291	±67	3299.5	±9.9	0	1.499	2.4	0.26970	0.60	1.501	2.4	0.26890	0.63	24.69	2.5	0.6660	2.4	0.967
KJR16.1	0.02	212	148	0.72	113.0	3105	±58	2986	±88	3108	±62	3269.8	±5.8	5	1.616	2.3	0.26403	0.37	1.616	2.3	0.26384	0.37	22.51	2.4	0.6190	2.3	0.988
KJR17.1	0.00	99	38	0.40	57.8	3353	±62	3430	±150	3347	±65	3289.8	±8.0	−2	1.466	2.4	0.26720	0.51	1.466	2.4	0.26720	0.51	25.14	2.4	0.6820	2.4	0.978
KJR19.1	0.97	96	61	0.66	52.2	3119	±59	2994	±91	3158	±64	3311.0	±11.0	6	1.584	2.4	0.27890	0.53	1.600	2.4	0.27070	0.71	23.24	2.5	0.6220	2.4	0.960
KJR20.1	0.05	180	93	0.53	97.3	3143	±58	3034	±92	3146	±61	3286.8	±6.3	5	1.590	2.3	0.26710	0.39	1.591	2.3	0.26670	0.40	23.11	2.4	0.6280	2.3	0.986
KJR11.1	0.02	219	151	0.71	133.0	3444	±63	3372	±140	3446	±67	3495.9	±5.3	2	1.416	2.3	0.30520	0.34	1.416	2.3	0.30500	0.35	29.70	2.4	0.7060	2.3	0.989

(1) Common Pb corrected using measured ^{204}Pb; (2) Common Pb corrected by assuming $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ age-concordance; (3) Common Pb corrected by assuming $^{206}Pb/^{238}U$–$^{208}Pb/^{232}Th$ age-concordance. Errors are 2-σ; Pb_c and Pb^* indicate the common and radiogenic portions, respectively; error in standard calibration was 0.87 %; common Pb corrected using measured ^{204}Pb (not included in above errors but required when comparing data from different mounts); d – discordance.

Table 3. Nd isotope measurements and calculations

Sample	K4	K5
Age (Ma)	3290	3290
Nd	19.7	19.2
Sm	3.40	2.72
Sm/Nd	0.17261	0.14197
$^{143}Nd/^{144}Nd_{today}$	0.51061	0.51024
$^{147}Sm/^{144}Nd_{today}$	0.10426	0.08575
$^{143}Nd/^{144}Nd_{i}$	0.50834	0.50837
$f_{Sm/Nd}$	−0.47	−0.56
T_{DM}*	3452	3394
$\varepsilon Nd_{t=3290\ Ma}$	−0.4	0.2
εNd_{today}	−39.6	−46.8

$f_{Sm/Nd}$ is the chondritic uniform reservoir (CHUR) normalized to the $^{147}Sm/^{144}Nd$ ratios and all calculations after DePaolo (1981).

indicates either crustal recycling (e.g. the granite is derived by partial melting of a metasedimentary source) or that the Keonjhargarh–Bhaunra pluton marks a craton border. However, a metasedimentary source is often indicated by granite ASI values above 1 (Frost *et al.* 2001) and would show low Rb/Sr (0.7 to 1.6) and low Sr/Ba (0.2 to 0.7) ratios, and a positive Eu anomaly (Harris & Inger, 1992), which is not the case here (see Table 1). Crustal thicknesses are not recorded for the Singhbhum craton, and it is still assumed that the Singhbhum granites intruded into the Iron Ore Group successions. However, the depletion in heavy REE (Fig. 2b) points to garnet in the residue of the melt, which could favour a thicker crust. To the south of our sampling area, lavas of the southern Iron Ore Group are up to 3.5 Ga and 3 km thick (Mukhopadhyay *et al.* 2008). Hence, significant basement thickness is required to support this lithospheric load. The tectonic and age relationships between the southern and western Iron Ore Groups remain unclear. Field observation allows the interpretation that the Singhbhum granite *sensu lato* intruded into the southern Iron Ore Group. However, it is not clear to which of the three phases these granitic intrusions can be related. Hence, the Keonjhargarh–Bhaunra pluton could, therefore, be interpreted as a crustal margin granite, in which case the southern Iron Ore Group may be related to a different Palaeoarchaean crustal block which amalgamated with the core of the Singhbhum craton during or after the 3.3 Ga magmatic event. The proposed crustal margin setting would explain the geochemical arc signature, the TTG characteristics and the relatively young T_{DM} in comparison to the crystallization age of the granitic body. A direct mantle source cannot be supported by the preliminary geochemical data and the low $^{143}Nd/^{144}Nd$ isotope ratios in comparison to mantle rocks (Saunders *et al.* 1988).

Clearly much more high-precision geochronological data are required from the Singhbhum craton as a whole in order to understand the geological evolution of this economically highly significant craton, and also to provide insights into early Earth processes and tectonic relationship of these Palaeoarchaean crustal blocks, as many of the older tectonic structures may well be masked by younger (post-Archaean) deformation. Interestingly, rather similar stratigraphic sequences to those of the Singhbhum craton are seen within successions of the Kaapvaal craton (De Wit *et al.* 1992). The very similar age constraints and crustal characteristics may indicate a relationship between these two early cratons during the Palaeoarchaean. The sedimentary pattern in South Africa preserved in Meso- to Palaeoarchaean rocks would allow for the vicinity of other cratons (Lowe & Byerly, 1999). In contrast, recent geochemical data from granites of the Bastar craton, located to the south of the Singhbhum craton in eastern India (Rajesh *et al.* 2009) suggest rather different crustal evolutions for the Bastar and Singhbhum cratons.

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